Phase-Referencing and the Atmosphere

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Outline:

- Basic principle of phase-referencing
- Atmospheric / astrophysical limitations
- Phase-referencing requirements:
- Practical problems:
  - dispersion problems and H2O seeing
  - proper phase-reference stars
  - time aspect and evolving objects
  - injection stability and vibrations for fringe tracking
  - instrumental errors on dOPD measurements
- Conclusions

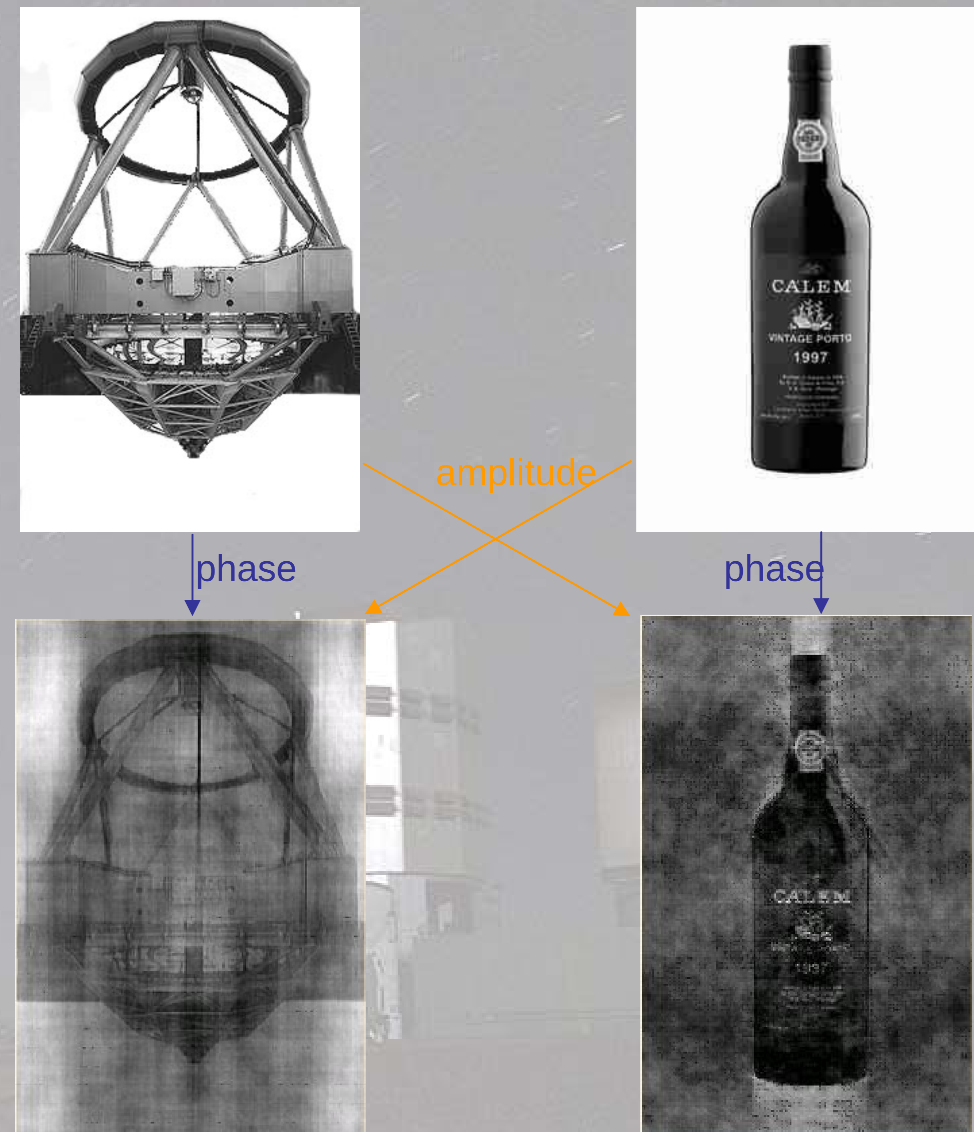
The importance of the phase

- Original images =>

- take their Fourier Transform
 => amplitude part (squared visibility)
 and phase part

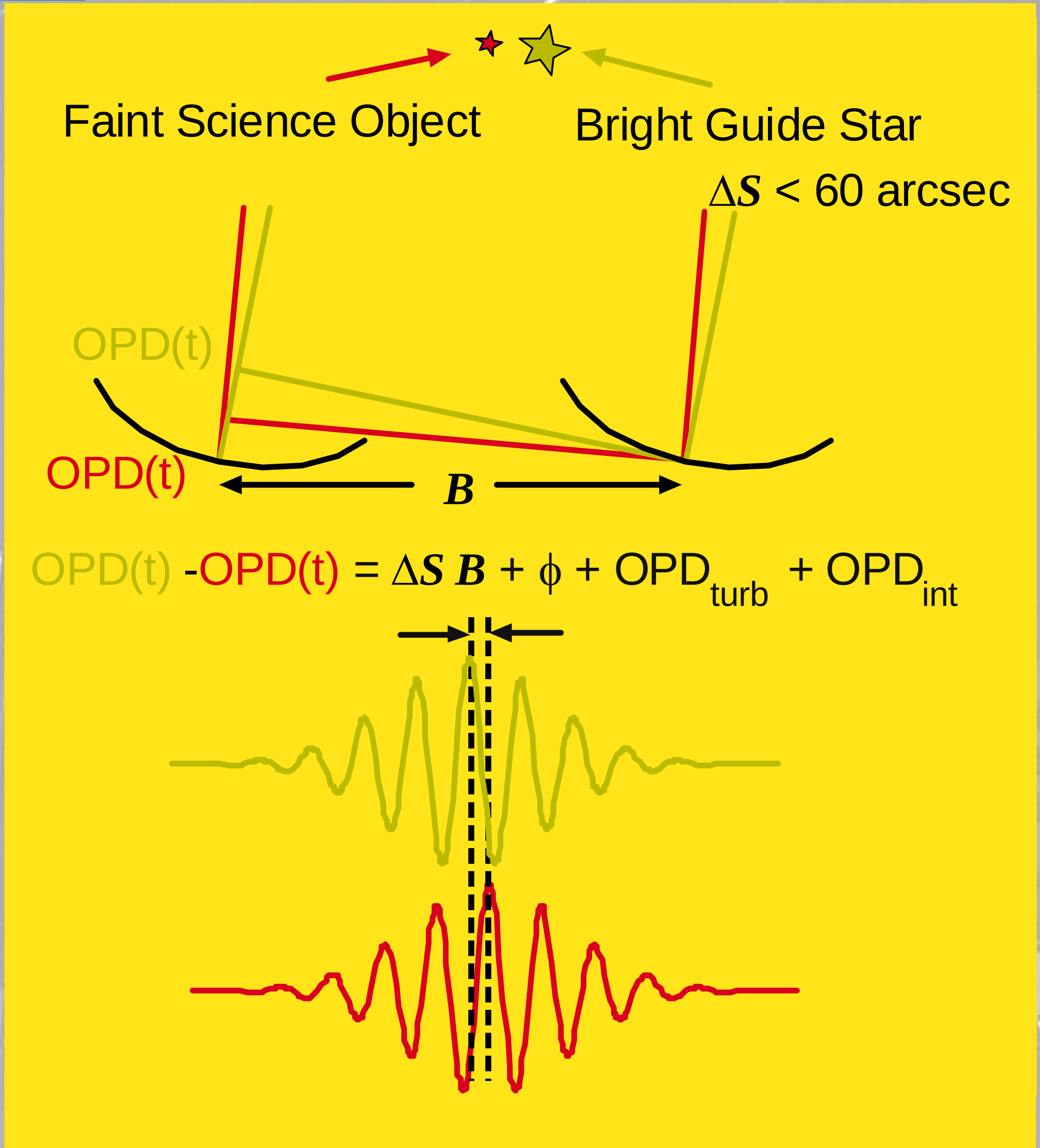
- cross the phase of one image with the amplitude of the other

- reconstructed images =>



Conclusion: the phase of the image contains the most important part of the information on its shape !

Phase-referencing principle



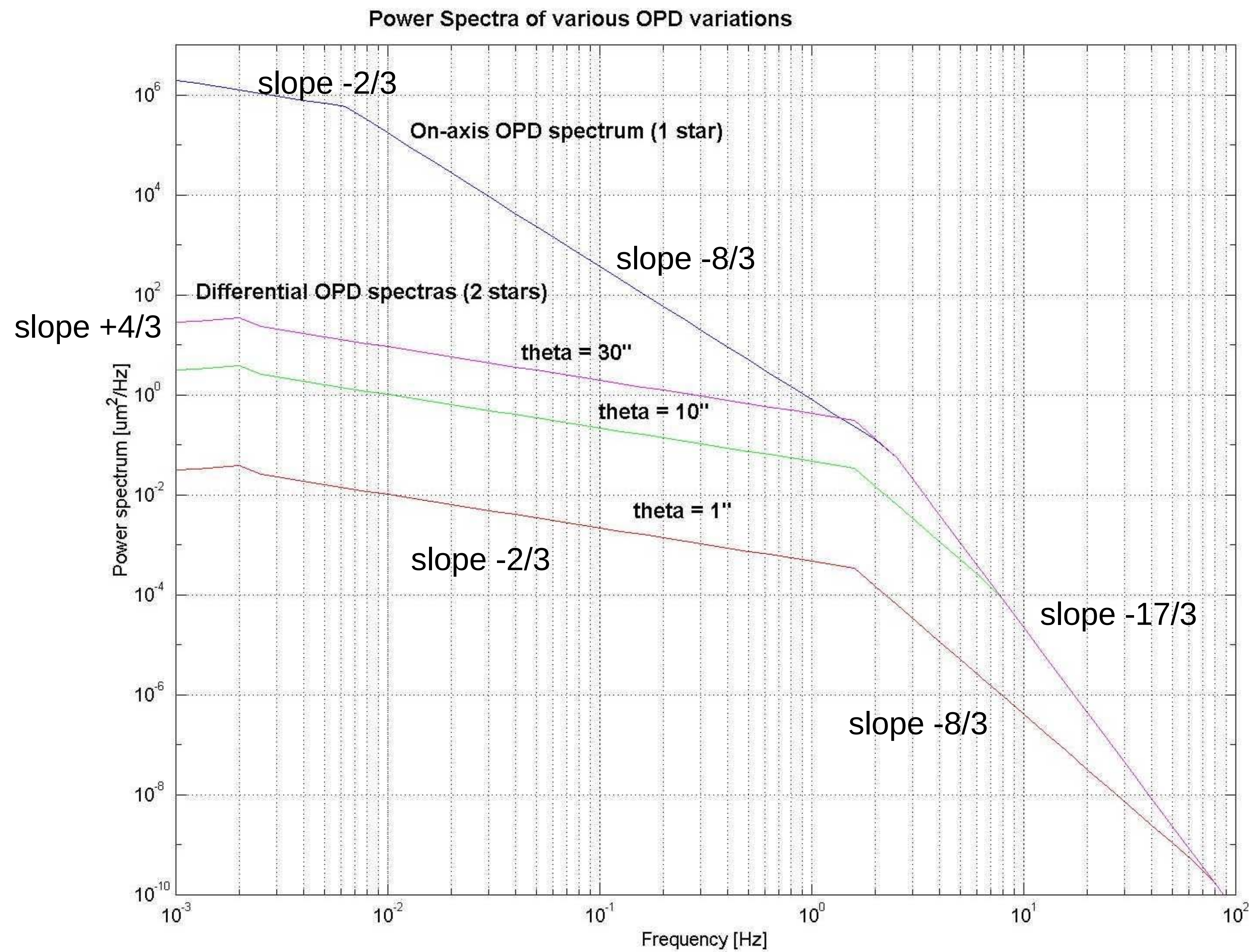
Δs = astrometry => goal of 10μas (planets...)

ϕ = imaging with high dynamic range (AGNs, star environment...)

=> needs to know the dOPD with nanometric accuracy

The limitations

Atmospheric anisoplanatism 1



Kolmogorov spectrum

Balloon measurements at Paranal

Seeing = 0.66” at 0.5 µm

τ_0 = 10 ms at 0.6 µm

Atmospheric anisoplanatism 2

- Off-axis fringe tracking <=> anisoplanatic differential OPD

$$\sigma_{OPDmeasurement} \cong 370.B^{-2/3}.\frac{\theta}{\sqrt{T_{obs}}}$$

for narrow angles (θ < 180" UT or 40" AT) and long total observation time T_{obs} >> ~100s

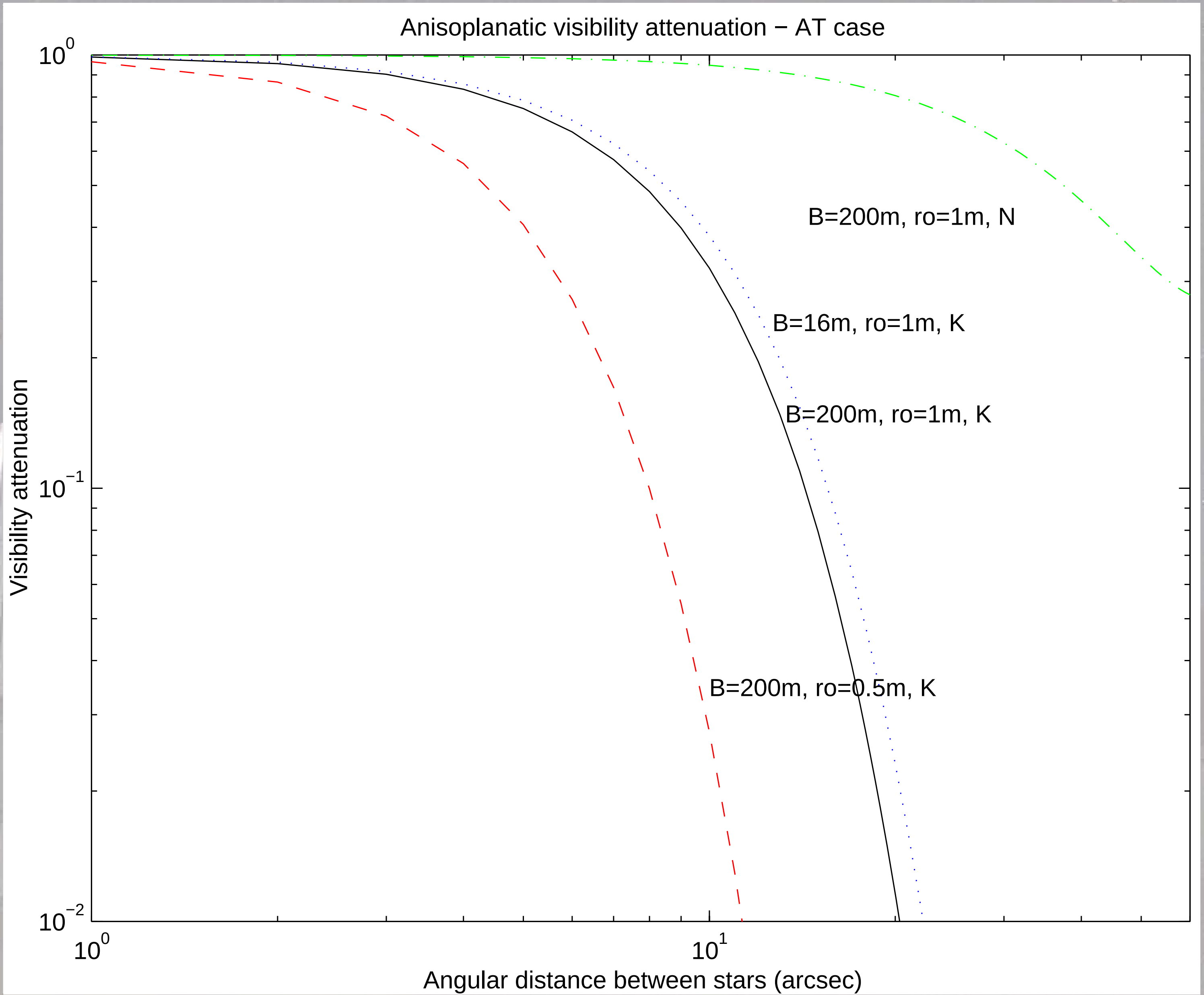
for Paranal seeing = 0.66" at 0.5µm, τ_0 = 10 ms at 0.6µm (L. d'Arcio)

Factor = 300 for Mauna Kea (Shao & Colavita, 1992 A&A 262)

  - Increases with star separation
  - Decreases with telescope aperture (averaging)
  - High impact of seeing quality
- Translates into off-axis maximum angles to limit visibility losses (< 50 to 90%):
  - K-band imaging (2 µm)
    - Bright fringe guiding star within 10-20"
  - N-band imaging (10 µm)
    - Bright fringe guiding star within 2'

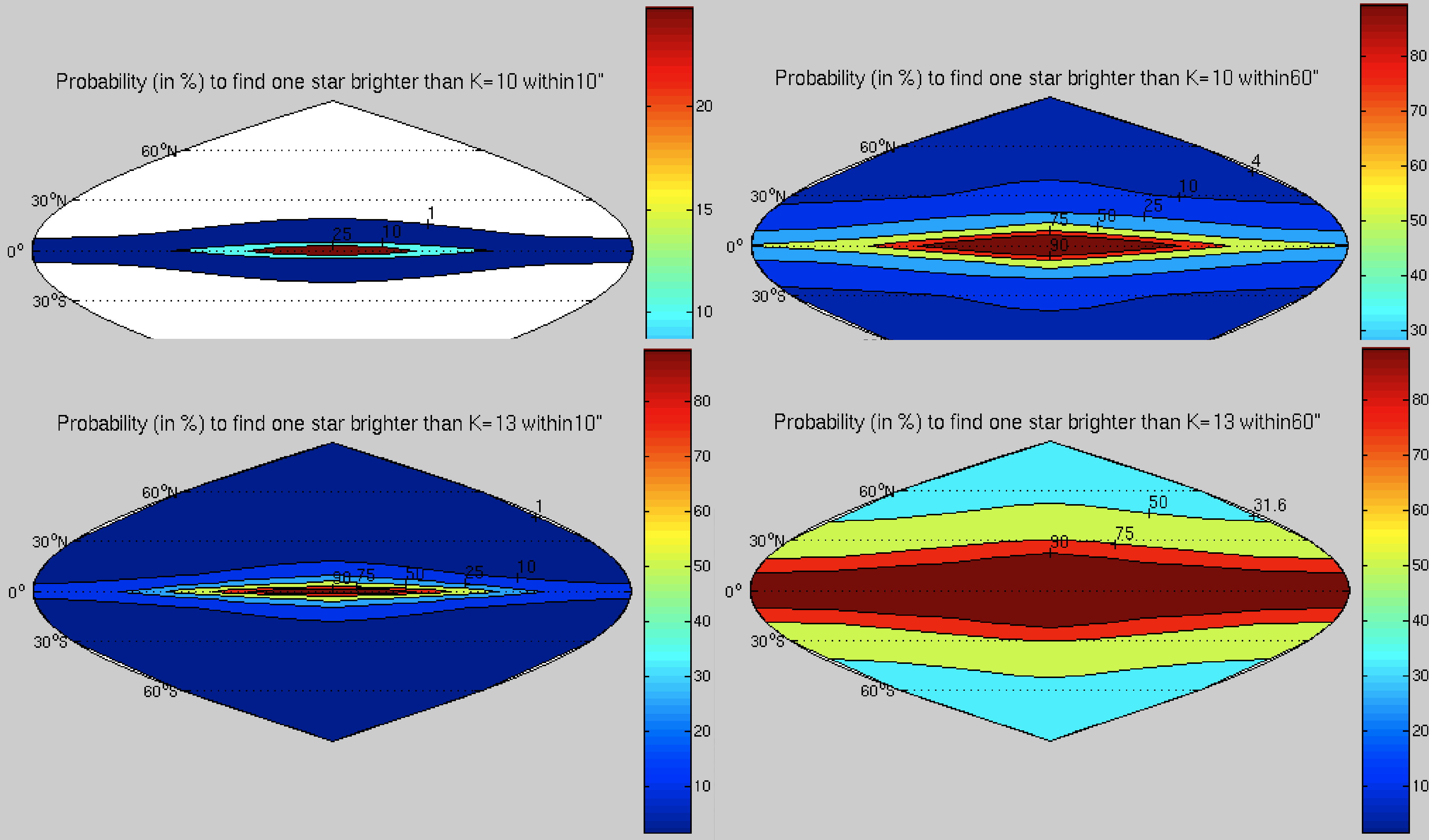
$$V = V_0.\exp\left[-2.\left(\frac{\pi}{\lambda}.\sigma_{residual\_OPD}\right)^2\right]$$

Anisoplanatism AT



Sky coverage

- Sky coverage <=> limiting magnitude



The requirements

- Phase-referencing measurable: difference of group delay

$$\Delta OPD = \Delta \mathbf{S.B} + \phi + OPD_{turb} + OPD_{int}$$

Fringe sensor — astrometry — imaging — atmosphere — Internal metrology

- Astrometric requirement
  - For 2 stars separated by 10” - 0.8”seeing - B=200m => Atmosphere averages to 10µas rms accuracy in 30 min
  - <=> 5nm rms measurement accuracy
- Imaging requirement =>
  - dynamic range is important (ratio between typical peak power of a star in the reconstructed image and the reconstruction noise level)
  - DR ~ $\sqrt{M} . \phi / \Delta\phi$ where M = number of independent observations
  - DR > 100 and M=100 <=> $\Delta\phi / \phi < 0.1$ <=> 60nm rms in K

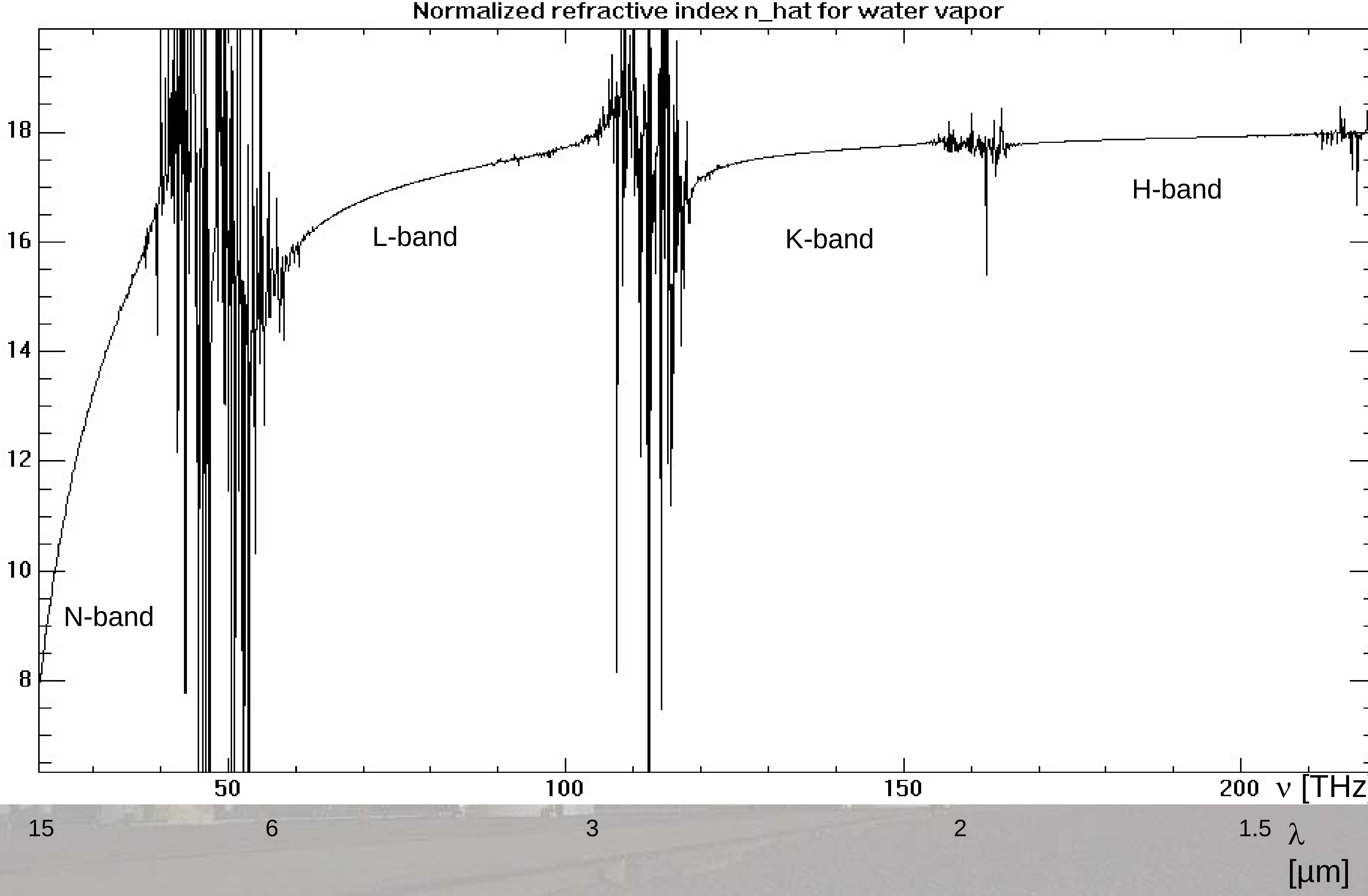
- Ability to do off-axis fringe tracking

The problems

Dispersion and H_2O seeing

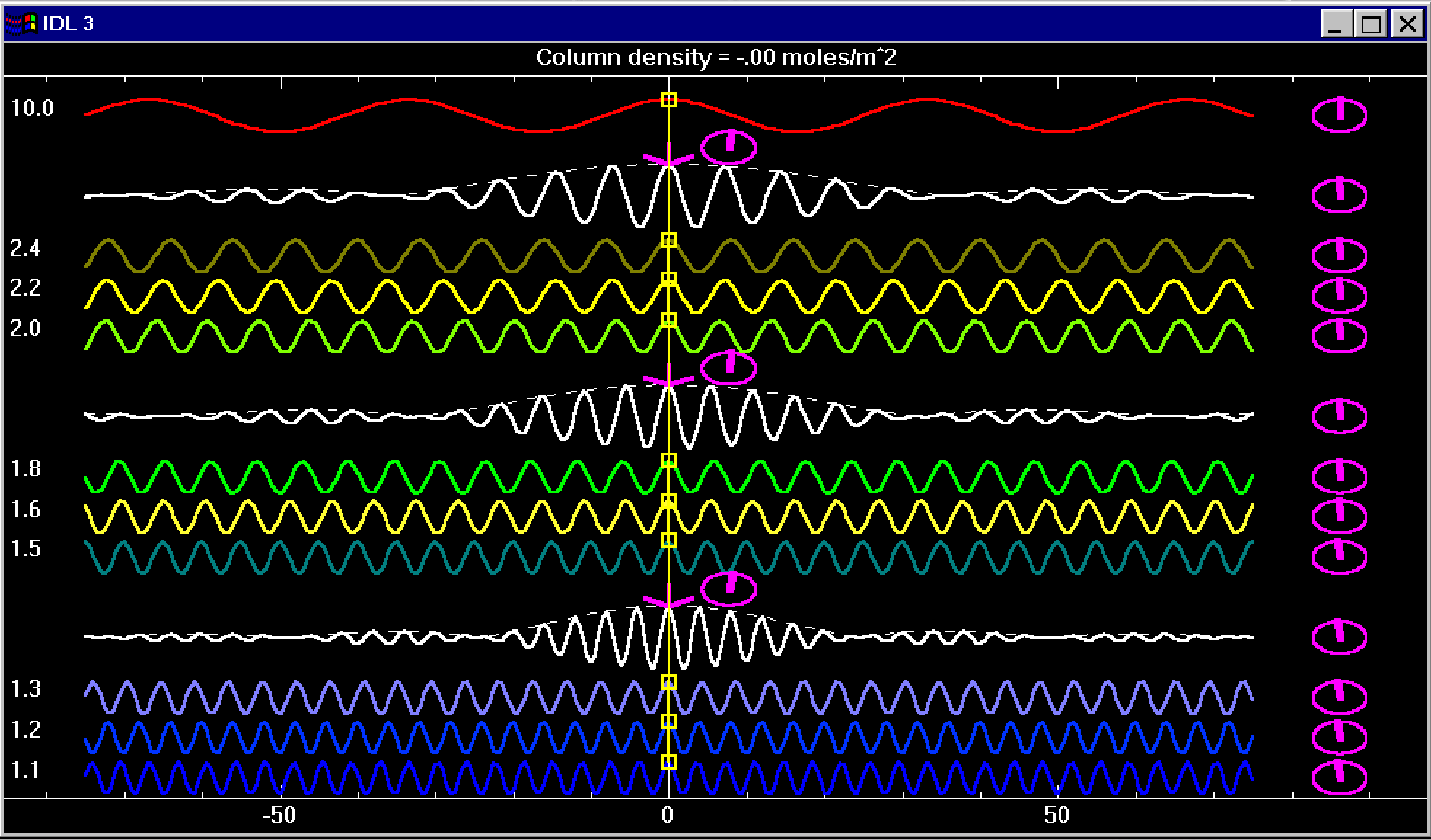
- Transversal & longitudinal dispersion
- Fringe tracking and observation at different λ
- Air index of refraction depends on wavelength =>
  - phase delay ≠ group delay
  - group delay depends on the observation band
  - fringe tracking in K does not maintain the fringes stable in J / H / N bands
- Air index varies as well with air temperature, pressure & humidity
  - overall air index dominated by dry air
  - H_2O density varies somewhat independently
  - H_2O effect is very dispersive in IR (between K and N)
- Remedy: spectral resolution

Refractive index of water vapor (©R. Mathar)



Dispersive effect between (and within) bands due to 0 – 600 mole/m^2 of additional dry air. (= 20 meter delay-line offset) (©J. Meisner)

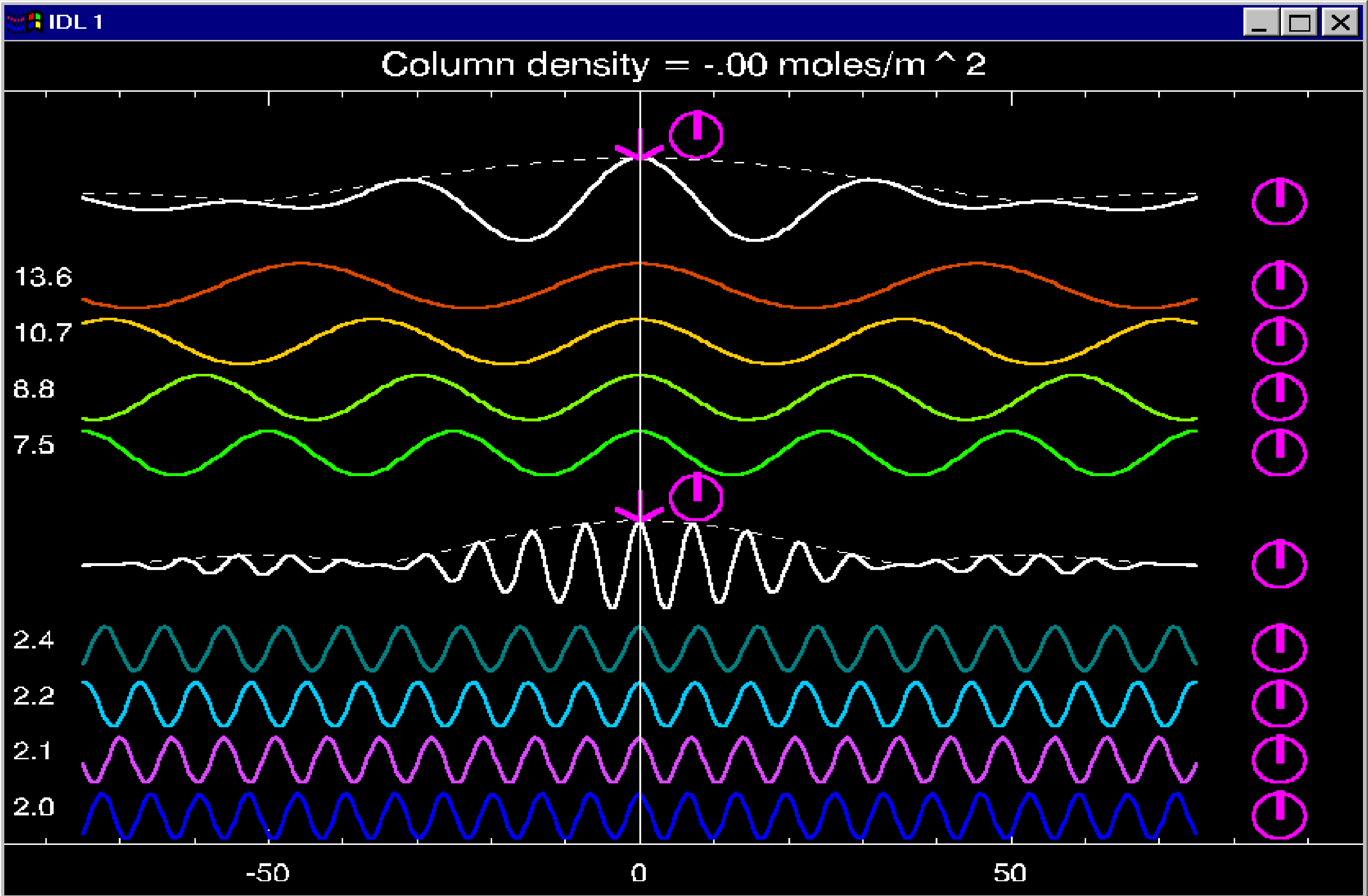
Note that dispersion from dry air increases rapidly at short wavelengths



(Tracking at the group-delay in K band)

Water Vapor dispersion, with phase-tracking at K band

0 – 5 moles/m² (typical p-p value due to atmosphere) (©J. Meisner)



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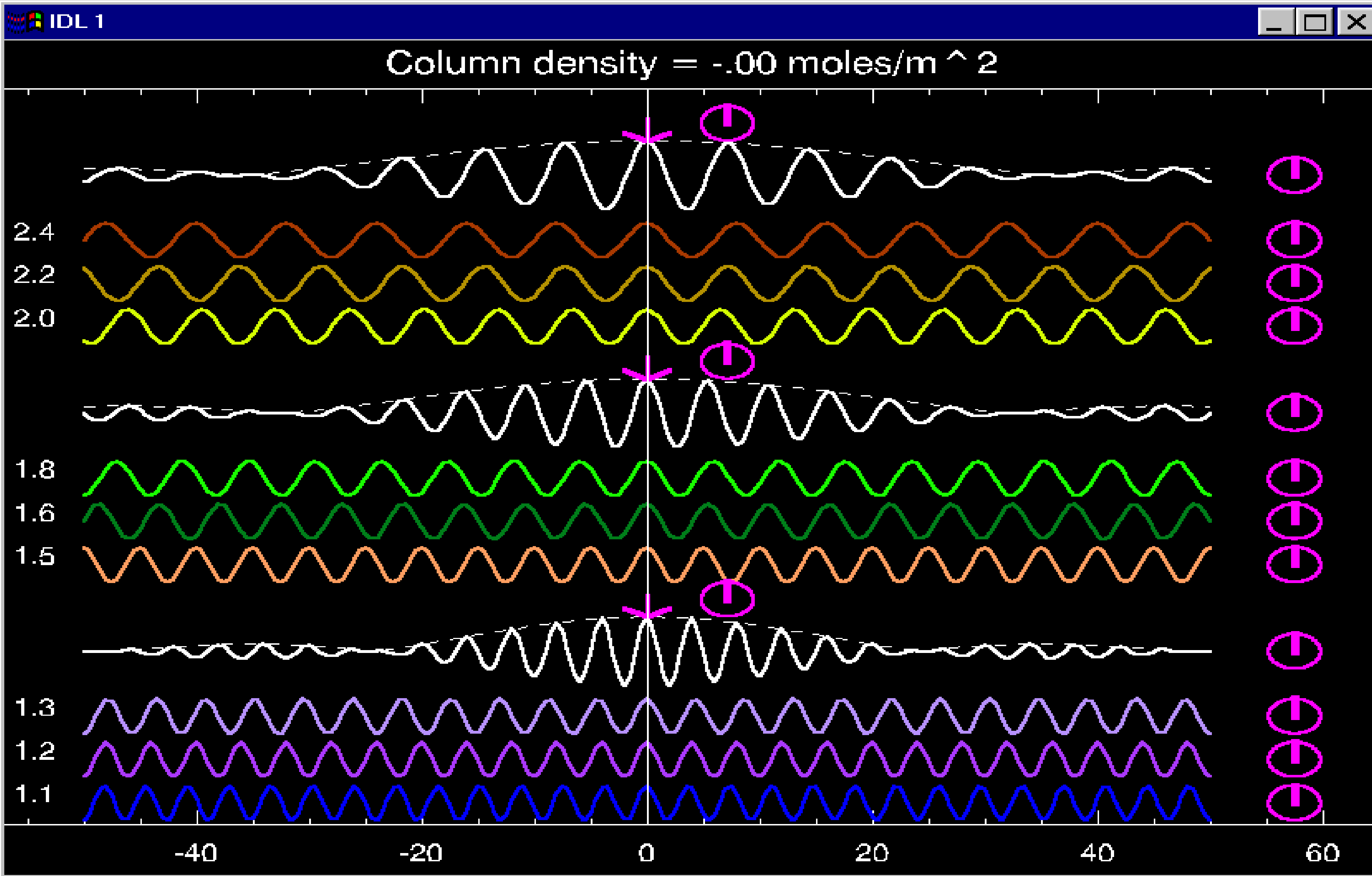


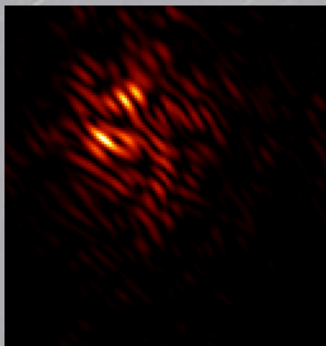
Proper phase references

- We want to do imaging =>
  - usually the scientific target is faint =>
    - Reference star must be bright (K<10 or 13)
    - Bright stars are close and big
  - need of long baselines
- => High probability that your guide star is:
    - resolved => low visibility
    - with resolved structures => non-zero phase
- Phase-referencing cannot disentangle between target phase and reference phase
- Remedies:
  - baseline bootstrapping
  - characterize your reference star (stellar type, spectrum, interferometry) as much as possible prior to observation
  - find a faint star close to the reference one to calibrate it

Time and evolving targets

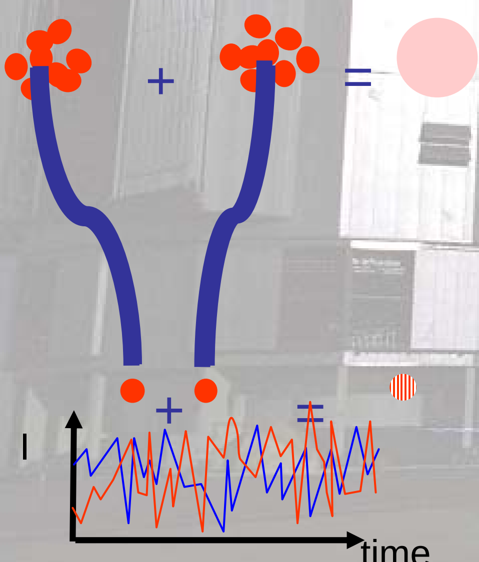
- Phase-referencing works with 2 telescopes at a time => Measurements of different u-v points are taken at different epochs
- If a baseline change needs telescope relocation, it can take time (one day up to several months)
- If the object evolves, it is a problem
- Remedies:
  - have fast relocatable telescopes
  - if the “evolution” is periodic (Cepheid, planet), plan the observations at the same ephemeris time
  - have more telescopes and switch from one baseline to another within one night
  - no snap-shot image like with phase cl□osure but better limiting magnitude

Fringe tracking problem nr 1: Injection stability

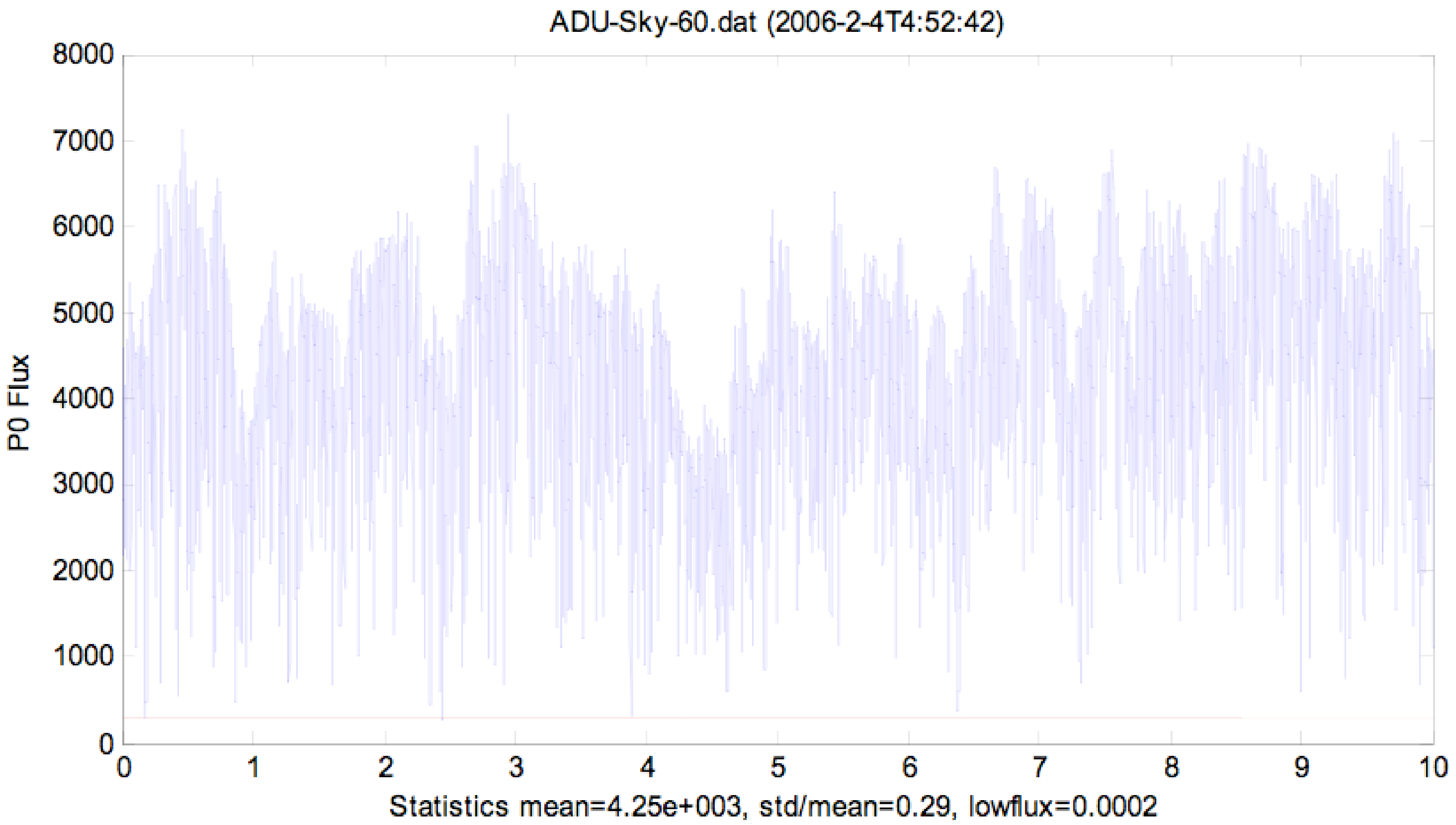


Spatial fringes for 2 UTs @ 2.2 μm seeing = 0.5”

- Only the “flat” part of the wavefronts interfere coherently, all corrugations and tilts give noise
- Use of monomode optical fibers as spatial filter
- Strehl ratio is not stable at 10 ms timescales
- Too few photons (<~100) => no fringe tracking
- Affects limiting magnitude & efficiency
- Remedies:
  - tip-tilt sensing close to the instrument & correction in closed/open loop
  - optimize the injection at the start
  - check continuously at low rate if the injection is still optimum to compensate for drifts between tilt sensor and instrument



Injection stability

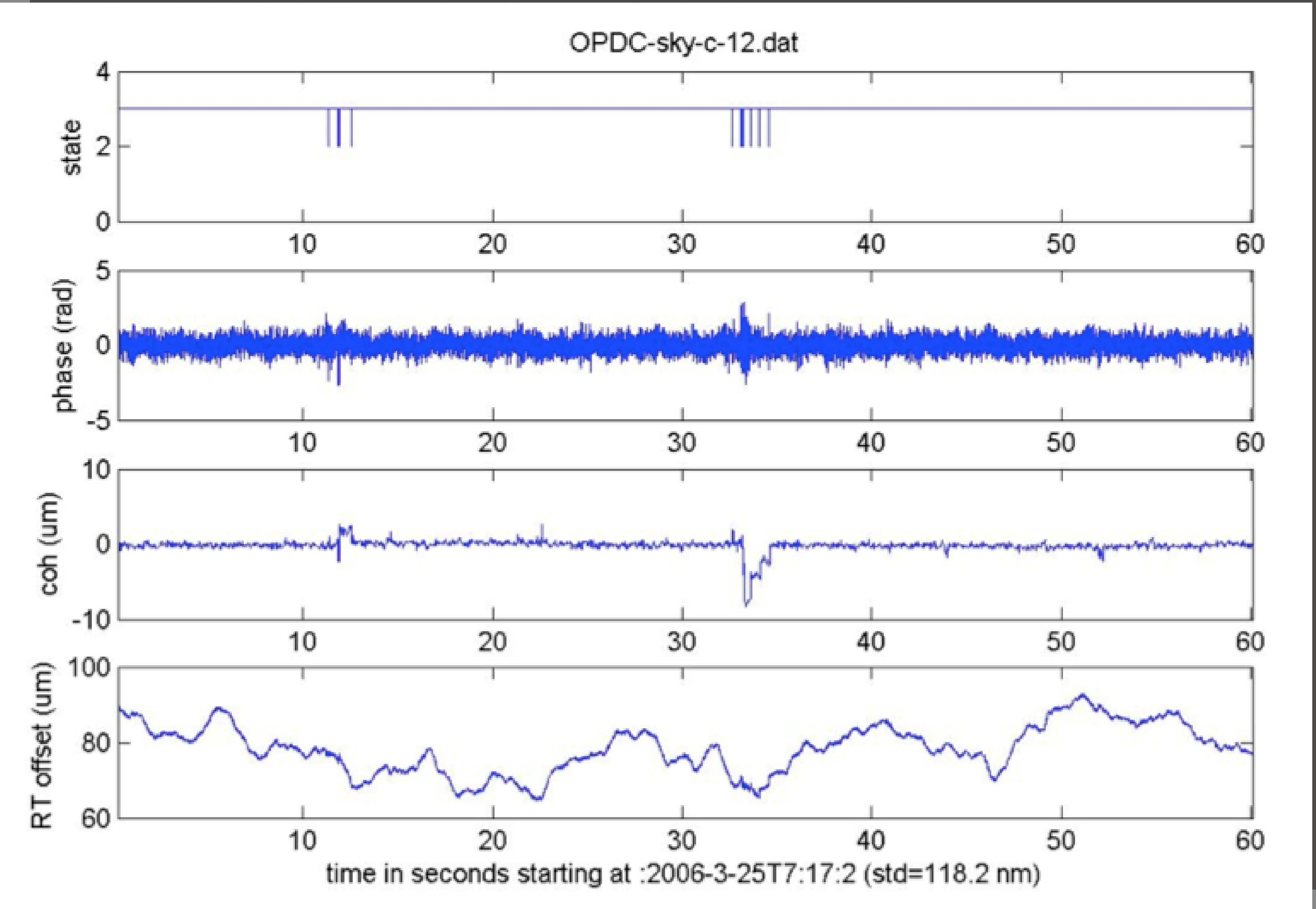


Fringe tracking problem nr 2: vibrations

- OPD instability due to vibrations affects
  - the capability to track fringes if too large / too fast
  - the accuracy of the fringe phase (if OPD scanning)
  - the fringe visibility (so the SNR) if fast and small
  - the OPD residuals
- Remedies:
  - Vibrations to be reduced at the source as much as possible:
    - passive damping,
    - active vibration control of well identified sources
  - Laser Metrology to measure fast (> 1kHz) the OPD between 2 telescopes from the telescope to the laboratory
  - Accelerometers and feed-forward for the mirrors not seen by the metrology

Fringe tracking can work: FINITO + MIDI + AT in March 2006

Seeing 0.99”, τ_0 = 4.2 ms, Hmag = 1.9



Other instrumental problems

- Baseline calibration:
  - baseline should be known at better than < 50µm
  - dedicated calibrations are needed
  - stability with time and telescope relocation to be verified
  - VLTI auxiliary telescopes: baseline can be calibrated at better than 40µm (limited by reference star position knowledge) and is stable at better than 120µm
- Telescope differential flexures:
  - everything that is not seen by the internal metrology must be very limited or modeled
  - second differential effect (2 telescopes - 2 stars)
- Mirror irregularities & beam footprints
  - non-common paths between internal metrology and stellar light should be minimized
  - bumps on mirrors should be avoided and mapped

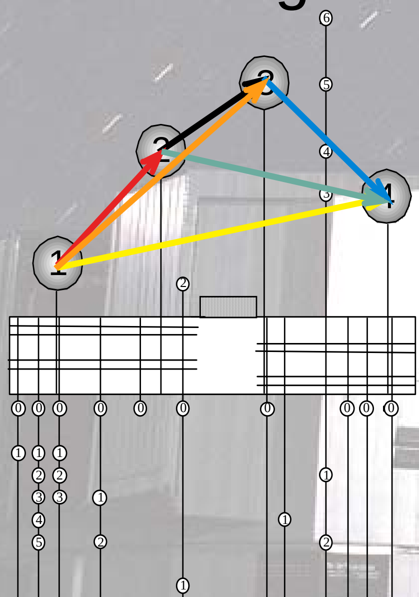
Conclusions

- Phase-referenced imaging is complementary to the phase-closure technique
- Both are essential if one wants to get images and even for model constraint imaging (provides critical constraints on the model)
- Data reduction software developed for radio-astronomy can be adapted
- Performances are mainly limited by:
  - the number of available baselines
  - the sky-coverage
  - the instrumental degradations of fringe tracking
  - the choice of proper phase references
  - the correct design of the interferometer (metrology,...)
  - the variable humidity of the atmosphere / tunnels

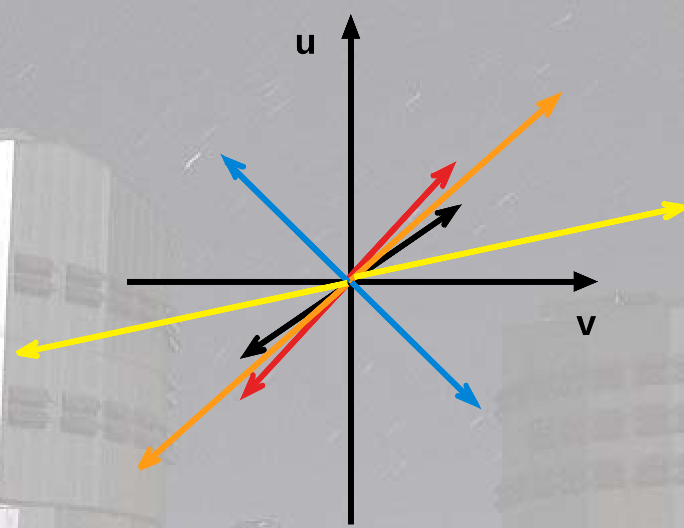
Additional slides

u-v plane and reconstructed PSF

- Image intensity: $I_{im}(\alpha) = \mathrm{IFT}\,(\,\Gamma(u_1 - u_2)\,)$ (inverse the Fourier transform)
  with $u_1 - u_2$ = baseline vector and Γ = complex visibility
- Good "synthetic aperture reconstruction" if good u-v coverage

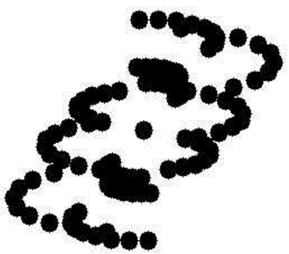


This is NOT the u-v plane

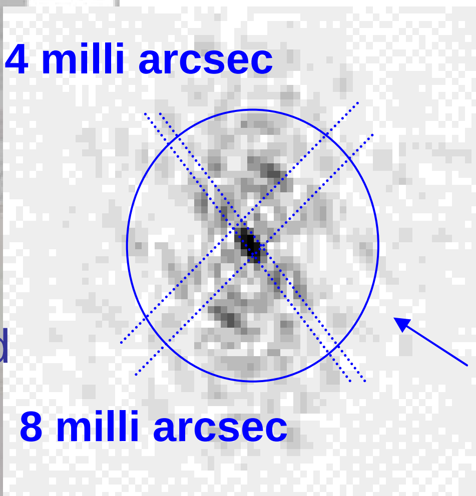


This IS the u-v plane

u-v coverage
(UT 8 hours δ=-15º)

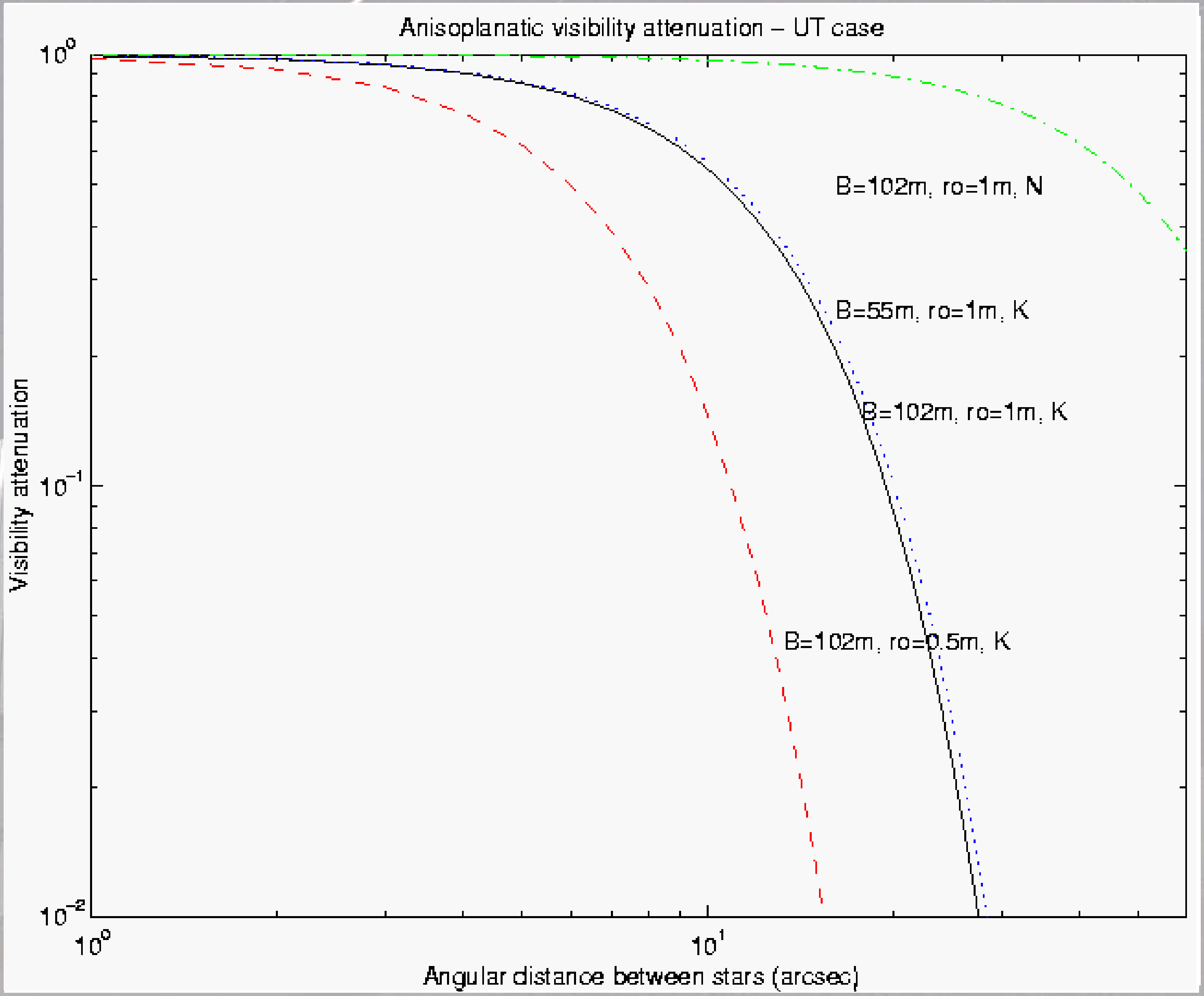


Reconstructed PSF
K-band



Airy disk
UT

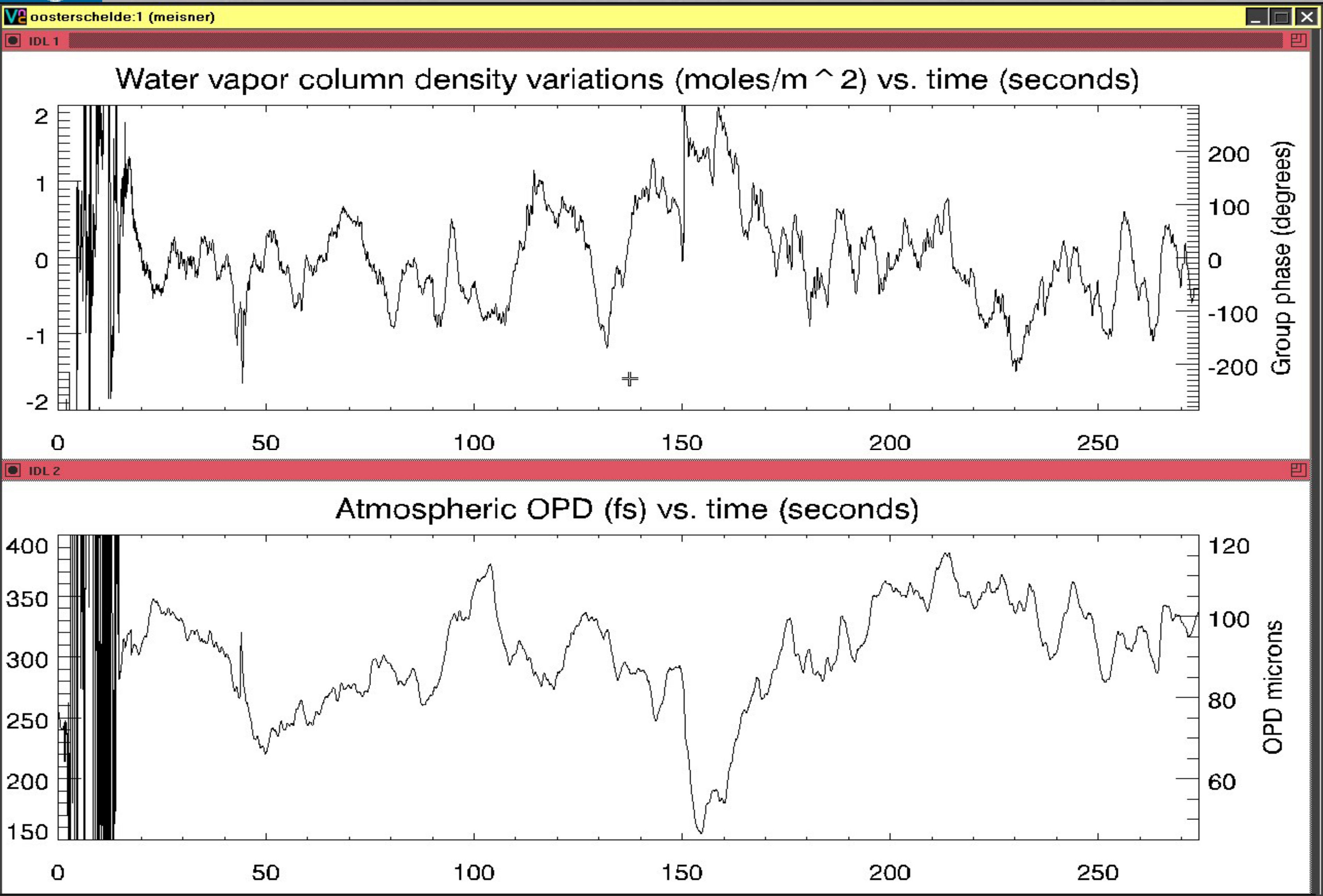
Anisoplanatism UT



Fringe tracking requirements

- Fringe tracking performance if limited by atmosphere:
  - Total closed loop residuals should not introduce more fringe visibility loss (5-10%) than typical anisoplanatism => < 100 nm rms total OPD residuals
  - $$\sigma_{residual\_OPD} \cong 2.54.10^{-6}.\frac{1}{D}.T^{11/6}$$
  - Fringe tracking residuals depend on control loop transfer function:
    - low bandwidth (45 Hz) => 100 nm - improved bandwidth (100 Hz) => 70 nm
- In practice, it is very difficult to reach => what is needed ?
  - K-band:
    - Residual OPD < 300 nm rms =>
      - 0.1% probability of fringe jumps in K-band
      - loss of visibility on instrument < 30% but can be calibrated
    - Larger residuals => fringe jumps to be recovered by group delay tracking => loss of SNR accelerates =>
      - larger observation time to get the fringes out of the noise: T ~ noise^2
      - difficulty to calibrate the visibilities
  - N-band:
    - Relaxed coherencing requirements: residual closed-loop OPD <~ 10µm rms
    - Accurate fringe position measurement for post-processing: OPD noise < 1µm rms

MIDI observation: OPD and water vapor (©J. Meisner)



Keck's results of dispersion extrapolation (©C. Koresko): estimated phase delay at 10μm vs. measured phase delay